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HUB AND SPOKE LOGISTICS FOR MARITIME PATROL AND RECONNAISSANCE OPERATIONS

by

Robert Love Robinson, Sr.

December 2011

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This research studies the ability of 11 combat logistics force (CLF) ships and four transport aircraft to support building and sustaining operations at four maritime patrol and reconnaissance military airbases throughout the African continent. We have implemented a traditional hub and spoke (H&S) concept with sample demand data provided by the staff of Commander, Patrol and Reconnaissance Force Seventh Fleet, in a hypothetical situation where U.S. forces are required to assist the Nigerian government. We use the CLF Planner optimization tool to obtain shuttle schedules for three scenarios of daily demands of four commodities. One scenario requires the buildup of an airbase within seven days, and the other two require so in three days. All CLF shuttles have been randomly selected, positioned and loaded with commodities. Depending on the length of the buildup phase and the initial stock of commodities at the H&S, we find that the continuous sustainment operations (over a 45-day planning horizon) may not be feasible in some cases. Specifically, if a short buildup phase is required, we recommend the prepositioning of commodities at a minimum of 25% of daily demands, and dedicated air shuttles carrying only ordnance.

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HUB AND SPOKE LOGISTICS FOR MARITIME PATROL AND RECONNAISSANCE OPERATIONS

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AIMD	Aircraft intermediate maintenance depot
AIP	Aircraft improvement program
ALGBG	Algiers, Algeria spoke
AOR	Area of responsibility
ASD	Aviation Supply Department
ASW	Anti-Submarine Warfare
ATDJ	Algiers to Djibouti, "Air" prime node
BuildUp	Build-up operations at Hub and Spokes
C17	Globemaster III (Type C17) Aircraft
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CLF	Combat Logistics Force
CTF-72	Commander, Patrol and Reconnaissance Force Seventh Fleet
DAKBG	Dakar, Senegal Spoke
DJIBG	Djibouti, Republic of Djibouti Spoke
GHZ	Gigahertz
GSE	Ground Support Equipment
GSF	Ground Support Equipment Diesel Fuel
H&S	Hub and Spoke
ISAR	Inverse Synthetic Aperture Radar
JP8	Aviation Fuel (Jet Propeller and type number)
LAGBG	Lagos, Nigeria Hub
MDA	Maritime Domain Awareness
MMA	Multi-Mission Maritime Aircraft
MPRA	Maritime Patrol and Reconnaissance Aircraft
MPRF	Maritime Patrol and Reconnaissance Force
MRC	Maritime Reception Center
OPLAN	Operational Plan
ORDN	Ordnance (includes all torpedoes, missiles, and explosives)
P3C	Orion Maritime Patrol and Reconnaissance Aircraft
P8	Poseidon multi-mission aircraft
PreOps	Pre Operations at Hub and Spokes
RAM	Random access memory
ROTA	Rota, Spain
ROTAA	Rota Air, Spain

S1, S2, S3	"Heavy BuildUp," "Minimum BuildUp," and "Minimum BuildUp with initial inventory" scenarios, respectively
SUW	Surface Warfare
Sustain	Sustainment operations at Hub and Spokes
T-AFS	Combat Stores Ship
T-AKE	Auxiliary Cargo and Ammunition Ship
TAO	Henry J. Kaiser-Class Ship
T-AOE	Fast Combat Support Ship
TAO-SH	Henry J. Kaiser-Class Single Hull Ship
UK-AORH	United Kingdom's Fort Victoria Class Replenishment Oiler

EXECUTIVE SUMMARY

Maritime patrol and reconnaissance aircraft (MPRA), a U.S. Navy asset, belongs to a community that has been a transformational force as it has adapted to changes in mission requirements. This research studies the ability of combat logistics force (CLF) ships and military transport (C17 aircraft) to support the building and sustainment operations at four MPRA military airbases: Djibouti, Djibouti (DJIBG); Dakar, Senegal (DAKBG); Algiers, Algeria (ALGBG); and Lagos, Nigeria (LAGBG), along with one maritime reception center (MRC) in Rota, Spain.

An MRC serves multiple functions, which include letting aircraft launched into joint operations areas conduct a mission enroute to its forward operating base, and leveraging "economy of force" efficiencies to support multiple theaters of operation through distribution of limited assets from secure locations.

We have implemented a traditional hub and spoke (H&S) concept with sample demand data from the staff of Commander, Patrol and Reconnaissance Force Seventh Fleet. We have used the CLF Planner, developed by students and faculty at the Naval Postgraduate School, to obtain optimal shuttle schedules for three scenarios. We hypothesize a message received from the Nigerian government requesting military assistance from the United States to build a coalition fighting force to help end the violent efforts of opposed Nigerian forces. The missions flown from each H&S are exclusive to that airbase and our model has focused on the sustainment of commodities. Although this study provides results for a Nigerian scenario, the methodology may be used for any region and scenario where the H&S concept is applicable.

Our H&S model is unique to CLF Planner, requiring customized coding in order to allow air shuttles to deliver commodities to the customers. CLF Planner uses multiple data inputs with precise coordinates and great circle navigation points to represent the sea routes and point-to-point air routes that service our H&S. We have represented the region's routes using 108 nodes and 177 undirected arcs. We, also, replicate 15 indiscriminant shuttles from six classes (six Henry J. Kaiser-Class Single Hull (TAO-

SH), one Auxiliary Cargo and Ammunition Ship (T-AKE), one Combat Stores Ship (T-AFS), two Fast Combat Support Ships (T-AOE), one United Kingdom's Fort Victoria class replenishment oiler (UK-AORH), and four C17s as air shuttles). All of our CLF shuttles have been randomly selected from a list of joint, allied and coalition forces. At the beginning of the planning horizon, shuttles have been randomly positioned throughout our theoretical area of responsibility and either loaded with the four commodities (aviation fuel (JP8), ground support equipment diesel fuel (GSF), ground support equipment (GSE), and military ordnance (ORDN)) required at the H&S or started empty. Specifically, four surface ships and all four C17s are loaded while the remaining seven surface ships are not.

We have tested three scenarios, S1, S2, and S3, respectively, of daily demands of each of the commodities over a 45-day planning horizon. Each scenario consists of three phases: buildup, pre-operations and sustainment. We assume a safety-stock level is reached if inventory falls 50% below its total capacity. The same is true for an extremis level whenever the commodity inventory falls below 25%. A penalty is applied when inventory levels fall below either measure, but a more stringent penalty occurs when below the extremis level. CLF Planner has produced computational results for each scenario with which decision makers may gain important insights in the planning of the operations supported from H&S.

In Scenario S1, entitled "Heavy BuildUp," we start with an empty airbase that needs to be built, within seven days, into a functioning hub (or spoke) that is capable of continued sustainment of MPRA missions. We meet 100% of the demands for the JP8, GSE, and GSF commodities for all but DAKBG, which still achieves 98% sustainment for both JP8 and GSF. While some shuttles work expeditiously in order to fulfill H&S's demands, the TAO_SH class shuttles are used only modestly because they cannot carry ORDN. The rest of the unmet demand is due solely to long transit times for all CLF surface ships.

Scenario S2 is referred to as "Minimum BuildUp" because we assume the buildup

phase must be completed in only three days. Our computational analysis shows that this results in a more difficult sustainment phase than in scenario S1: All commodities for all H&S spend more days below extremis levels.

S3 has the same "Minimum BuildUp" requirements as in S2. However, we assume dedicated ORDN air shuttles and pre-positioning of commodities at the extremis level at the beginning of the planning horizon. All demand is met during the sustainment phase. We conclude that our two additions from S2 to S3 help create a tailored solution to logistical concerns within the MPRA community. We recommend this scenario for MPRA operations employing the H&S concept as it may be used for other regions and scenarios to identify critical commodities to pre-position.

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I.   INTRODUCTION

Commander, Patrol and Reconnaissance Force Seventh Fleet (CTF-72) has an ongoing requirement to provide maritime patrol and reconnaissance aircraft (MPRA) to conduct intelligence, surveillance, and reconnaissance missions in the Pacific and Central Commanders' areas of responsibility (AORs). Missions may also include anti-submarine warfare (ASW), surface warfare (SUW), inverse synthetic aperture radar (ISAR), mining warfare, and enhanced maritime domain awareness (MDA). Transportation of aviation fuel, food and dry stores, and ordnance from a supplier, the maritime reception center (MRC), to several hub and spokes (H&S) is required in order to support these responsibilities. This thesis studies the sustainment of these logistics demands via Globemaster III (C17) aircraft and combat logistics force (CLF) resources.

Prior to operational plan (OPLAN) execution, pre-positioning of MPRA and their logistics equipment and personnel to forward bases is required. Important aspects to be considered include: (a) building up logistics support for each airbase; (b) sustaining logistics demands at each location; and (c) relocating personnel and equipment in the event of destruction of any of the active H&S locations upheld by MPRA. This research focuses on the entire sustainment effort to include the transport of ground support equipment (GSE) and utilization during OPLAN progression involving MPRA (CTF-72, 2009).

Currently, the aircraft intermediate maintenance depot (AIMD) along with the aviation supply department (ASD), onboard most naval air stations, help provide storage of many weapons, parts, maintenance materiel and all the necessary logistics items to keep aircraft operational. The MRC is the central hub designed to stock supplies for the entire AOR and distribute logistics to the ASD in which then AIMD keeps MPRA fully mission-capable for each flight, or sortie.

There are primarily two critical elements recognized in maritime patrol and reconnaissance forces (MPRF): command and control (C2) and logistics. This thesis explores the optimal sustainment of logistics requirements at H&S, that is, how CTF-72

may best benefit from the use of C17 aircraft and CLF ships to keep H&S fully operational and engaged in the missions they must accomplish.

A.   HUB AND SPOKE AIR BASES

1.   Overview

The H&S model is intended for routine and expeditionary operations. The concept comes from the passenger and freight air carriers' idea of a central hub and multiple spokes that feed directly from the hub to each location (Dobson and Lederer, 1993). Also, this design is intended to allow travel from within spokes. The H&S model involves an expeditionary power projection operation formulated by the staff of CTF-72 (Figure 1). For this research, we assume each H&S will be collocated with a U.S. Navy MPRA airbase.

Since MPRA are land-based aircraft, their locations are analogous to "primary" and "expeditionary" airbases. A hub may occupy more space and be able to support MPRA, to include fuel supply, sonobuoys, weapon load-outs (torpedoes and missiles), emergency GSE, etc. A spoke would be required to maintain similar supplies but its capacity may not exceed the total (aircraft or essential personnel) count of a hub. H&S should be carefully selected to ensure continued operations based on threat level and possible enemy attack. Some considerations when creating a hub or spoke are:

1. Its relative location with respect to the AOR (in particular, MPRA transit time);
2. Its ramp capacities (aircraft and equipment);
3. Its capabilities to support emergency and/or distressed joint or coalition aircraft;
4. Its weather, which may affect the availability of the location; and,
5. Its ability to be relocated for different operations.
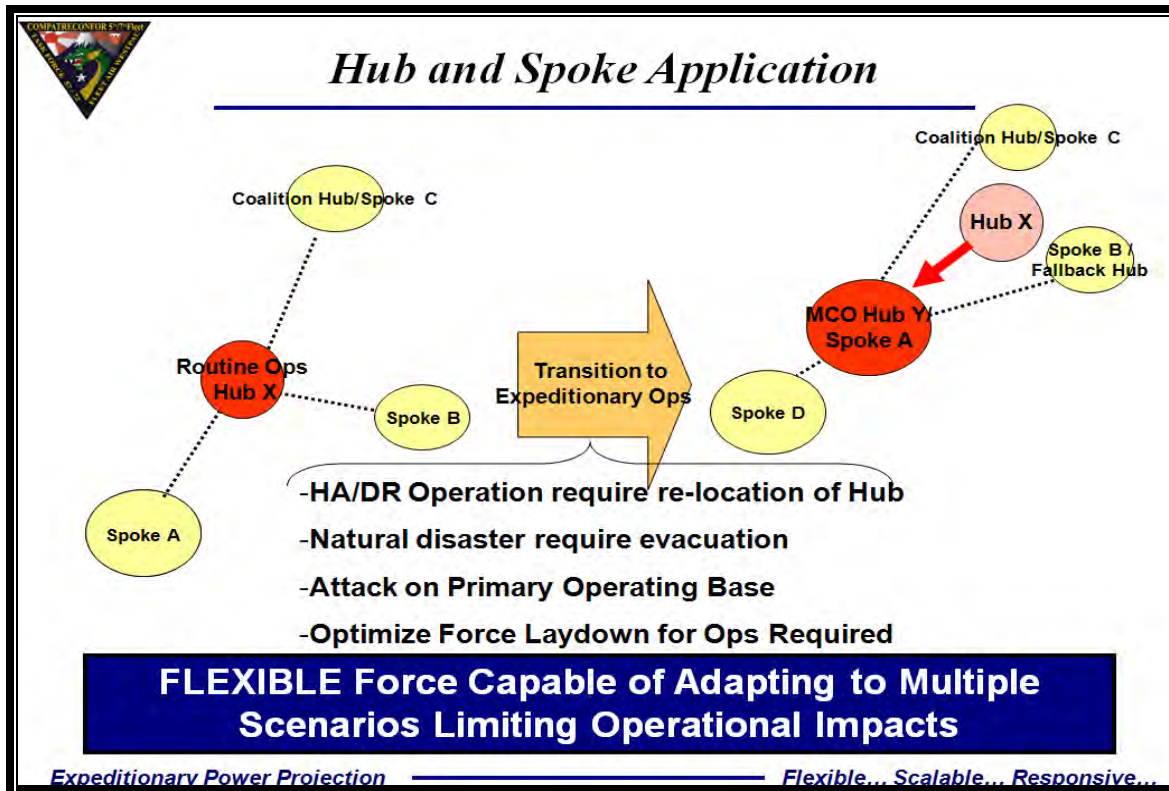
Figure 1. Hub and spoke schematic. This emphasizes the importance of expeditionary power projection as being flexible, scalable, and responsive. This figure also displays the routine operations (RO) tree with branches as either hubs or spokes. The depicted transition phase shows the crossover from RO to major combat operations (MCO). Within the MCO tree are branches similar to RO but we also note the collocated hub and spoke "C," which is designed to serve coalition operations. The fallback hub is designed to become operational within 72 hours in the event a current hub or spoke is destroyed or refocus on the HA/DR (humanitarian assistance and disaster relief) missions. (CTF-72 2009.)

The H&S idea is intended to differentiate between a mobile (primary) hub and expeditionary spokes that are expected to be operational within 72 hours of their positioning in the AOR. "A hub provides operations, logistics, maintenance and the data analysis center for current operations while the expeditionary spokes provide forward, ready-response forces detachable to remote locations" (CTF-72, 2009). The overall concept allows theater surveillance and reconnaissance operations without permanently constructed infrastructure (Figure 2).

2. Hub Capabilities

"The Navy's maritime patrol and reconnaissance forces must be postured to sustain and advance a broad, competitive advantage over emerging 21st century threats, and the MPRA community must enhance core mission capabilities with intelligence, surveillance, and reconnaissance capabilities that in turn support the Navy's transformation roadmap also known as Sea Power 21" (Osborne and Prindle, 2003). A hub for MPRF expeditionary warfare is used to provide a solid C2 platform while conducting sustainment operations. One of the primary capabilities of a hub is its support of the Chief of Naval Operations vision for the expeditionary maritime strategy. It is essential that aircraft support (maintenance control and/or AIMD) provides mission-capable aircraft for their continuous usage during OPLAN execution missions. Hubs are not only designed to ensure superior effort in MPRA mission sets, but they also provide a C2 service center as well as coordinated operation nodes for other task-force, joint, and/or coalition commanders in the fleet. One example of such an operation is observed during dynamic targeting exercises where the U.S. Navy and U.S. Air Force collaborate to designate targets from within their central hub. Once the targets are nominated, effort is then directed toward the best strategy to defeat that target whether by naval or air force assets. C2 is established and the controlling authority, derived at the hub, takes the lead and provides the action required to complete the sortie. Coordinated operations evolutions show that the utilization of a hub has value in the overall expeditionary maritime strategy.

Figure 2. Hubs snapshots. This display is of operations centers along with logistics, maintenance and data analysis centers. The figure includes merged pictures from the H&S slides contained in the Master Expeditionary Overview briefs given in Misawa, Japan (CTF-72, 2009).

3.   Spoke Capabilities

The vision and responsibilities of a hub remain the same for spokes (Figure 3). However, these are expected to achieve sustained operations while serving as a mobile C2 node for MPRF detachments (CTF-72, 2009). Due to their smaller size, spokes have the flexibility to relocate for multi-mission operations with less notice than hubs. A spoke is also designed to be a communications loop between MPRA and the fleet, supplying electronic "indications and warnings" signals amongst them.

Figure 3.   Spoke snapshots. These are depictions of spokes that provide forward, ready-response forces that are presumably easy to construct or remove during mobility operations. This figure includes merged figures taken from the H&S slides contained in the Master Expeditionary Overview briefs given in Misawa, Japan (CTF-72, 2009).

4. MPRA: P3C and P8 Aircraft

Over the years, the MPRA community has been a transformational force as it has adapted to changes in mission requirements: ASW from World War II through the Cold War to today; SUW and strike group coordinated operations as we faced the Soviet threat at sea; command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) capability demonstrated during operation Desert Storm; and ongoing operations in Afghanistan, Iraq, and throughout the Persian Gulf (Brooks, 2003). The demonstrated capabilities of the MPRA community will continue to be fielded with the current Aircraft Improvement Program (AIP) for the Lockheed Martin P3 Orion (P3C) aircraft (Figure 4), which completes the modernization of the force and takes it through the transition to multi-mission maritime aircraft (MMA). Equipped with new

data links and sensors, the AIP-equipped P3C has once again played a key role in ASW, SUW, MDA, ISAR and C4ISR in joint operations in Bosnia, Kosovo, India, Korea, Iraq, Afghanistan, the Philippines and many other countries, as detachments, in support of operations Enduring Freedom and Iraqi Freedom.

Figure 4. P3C Orion. This aircraft was assigned to the "Red Lancers" of Patrol Squadron Ten, VP-10. The figure is of Combat Aircrew Seven and Executive Officer taxiing home from a Seventh Fleet deployment in December 2007 (photo taken by a family member of the author in Brunswick, Maine).

As we move towards MMA, The P8 Poseidon (Figure 5), will truly be revolutionary in nature and transform the MPRA's future. Today, various models and upgrades of MPRA are strategically placed throughout the world and in every AOR.

Figure 5. P8 Poseidon multi-mission aircraft. (Facebook, 2010.)

B.   GENERAL ASSUMPTIONS AND CHAPTER OVERVIEW

For this research, our scenarios only involve select countries on the African continent. The above-mentioned missions are some of the many responsibilities MPRA and MMA fulfill on a daily basis. We provide a more detailed description later in this document.

Our MPRA is assumed to carry a full P3C crew of five officers and six enlisted persons, a load of 48 external and 36 internal sonobuoys, and minimal support equipment from its home station, in the continental U.S., to its designated H&S abroad. Once the H&S are occupied, our goal is to determine which assets better optimize H&S' sustainment to meet demand of sonobuoys, fuel, weapons and other logistics equipment required to carry out MPRA missions.

This research also makes the following assumptions:

a. The locations of the H&S bases are known, i.e., problem inputs;

b. The set of air and sea shuttles that may visit each H&S is known; and,

c. H&S capacities, as well as each location's mission set and daily operational requirements, are known. Daily demand for fuel, ordnance and stores vary for pre-operations ("PreOps"), build-up ("BuildUp"), and sustainment ("Sustain") stages with the given planning horizon of 45 days.

The remainder of this document is organized as follows:

In Chapter II, we describe the development of our scenario layout using CLF Planner, a tool developed by faculty and students at the Naval Postgraduate School (Brown and Carlyle, 2008). Chapter III describes additional scenario constraints and overall CLF Planner inputs, and explains CLF Planner outputs. Chapter IV comprises our different scenario excursions and computational results analysis. Conclusions and recommendations appear in Chapter V.

II. SCENARIO DEVELOPMENT AND CLF DESCRIPTION

A. THE HUB AND SPOKE SCENARIO

Our scenario hypothesizes a message received from the Nigerian government requesting military assistance from the U.S. The message infers that help is needed to curtail the violence of opposed Nigerian forces. Protection is needed off the shores of Bonny, Nigeria (Figure 6) to ensure maritime oil interests as well as oil pipelines along the Niger River are secure. Nigeria's military is heavily engaged in Sudan and cannot bring its forces home without increasing casualties and/or creating instability there. The United Kingdom has offered limited military support. In support of this request, the U.S. has set up a central hub in Lagos, Nigeria, to sustain this mission. The operating area is south of Bonny, 300 nautical miles away from Lagos. That distance equates to an approximate one-hour transit time for MPRA to conduct the requested operations. We assume MPRA missions average 10–12 hours in length, thus an eight-hour continuous coverage flight is the objective for each aircraft within the operating area. Also, expected turnover of MPRA is hypothesized to ensure that continuous coverage.

Figure 6. Hub travel chart to Nigeria. This charts shows our tactical situation depicting the operating area off Bonny, Nigeria, along with allied and enemy forces' locations. The current position of three enemy Nigerian boats (two Defender Class, "PBF," and a Combattante, "PGGF"), two blue force ships (LCS, "littoral combat ship" and Mk (Mark) 9, "FSM"), and the Bonny offshore terminal appear within a rectangular area of interest. The route shown from Lagos to the operating area is 280 nautical miles in length and considered the transit distance of MPRA from the hub. [Photo generated in Google Earth with overlay by Kline, 2009.]

We consider four MPRA airbase nodes (the above hub in Lagos, and three spokes) throughout the African continent (Figure 7) to:

a. Transit and support the Nigerian government from Lagos, the primary airbase;

b. Aid in the eradication of piracy via Djibouti (Djibouti) and Dakar (Senegal);

c. Complete strike group coordinated operations, ASW, and SUW missions from Djibouti, Algiers (Algeria), Dakar and Lagos; and,

d. Complete MDA missions with the use of the C4ISR suite primarily from Algiers. In addition, we assume each base will have its own AIMD and ASD, and Rota (Spain) is the MRC.
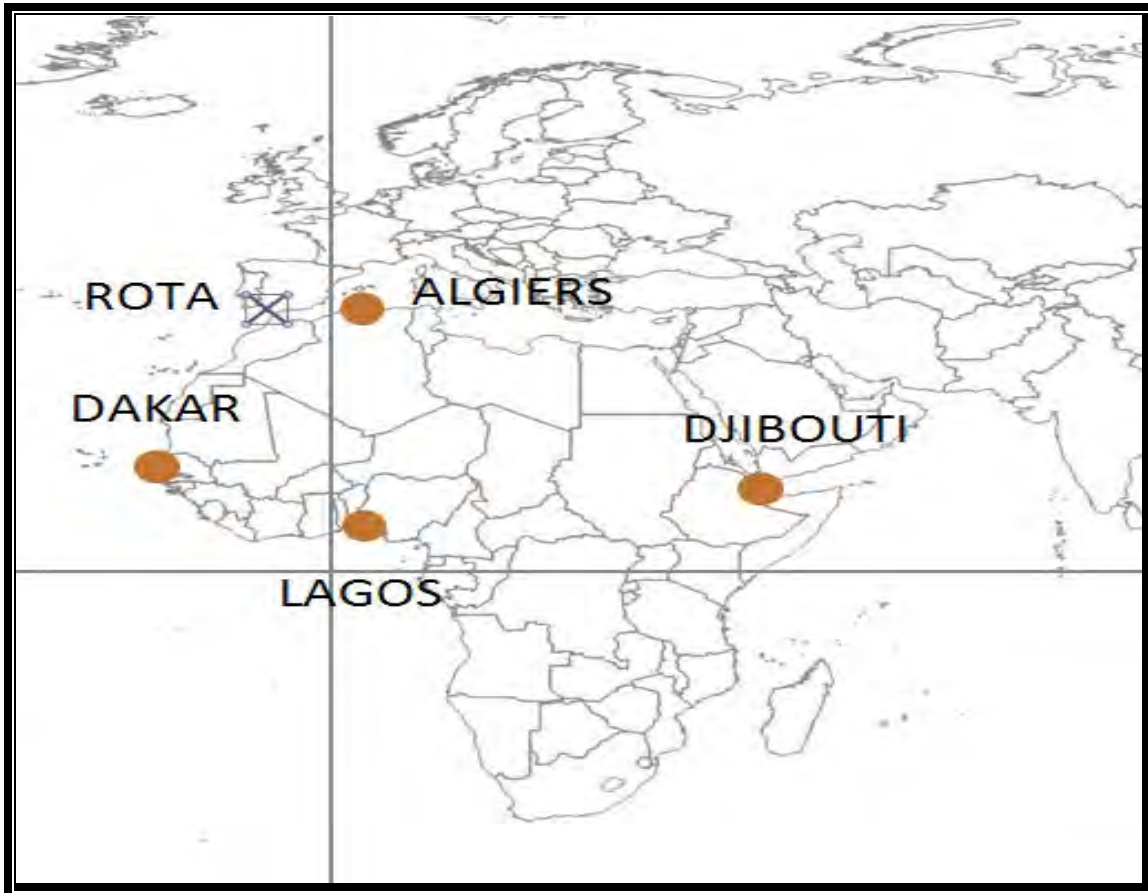
Figure 7. CLF Planner screenshot of H&S locations for our scenario. Lagos, Nigeria (hub); Dakar, Senegal (spoke); Djibouti, Djibouti (spoke); and Algiers, Algeria (spoke). Rota, Spain is the MRC.

For clarity, the MRC, AIMD, and ASD serve the following duties (CTF-72, 2009):

1. Maritime reception center:

   a. Enables maritime expeditionary operations in support of the full range of military operations;

   b. Fits the existing reception, staging, onward movement, and integration model for lines of communication to all the forces;

11

    c. Provides centralized location for theater briefings to aircrew and support personnel during their induction to the theater;

    d. Allows aircraft launched into joint operations areas to conduct a mission enroute to its forward operating base; and,

    e. Leverages "economy of force" efficiencies and existing logistics air heads to support multiple theaters of operation through distribution of limited assets from secure locations.

2. Aircraft intermediate maintenance depot is responsible for and conducts:

    a. Engine repair;

    b. Propeller repair;

    c. Airframe and landing gear repair;

    d. Avionics and armament repair ;

    e. Survival gear support; and,

    f. Support equipment maintenance.

3. Aviation supply department functions are:

    a. H&S pack-up kit management, and

    b. Shipping and receiving of all packages.

B. THE COMBAT LOGISTICS FORCE PLANNER FOR HUB AND SPOKE SUSTAINMENT

"The Navy CLF consists of about 30 special transport ships that carry ship and aircraft fuel, ordnance, dry stores, and food, and deliver these to client combatant ships underway, making it possible for U.S. naval forces to operate at sea for extended periods" (Brown et al., 2009). The CLF planning model is a mixed-integer, linear program that minimizes the total number of short-ton-days the combat fleet experiences with stock levels below safety stock in four basic commodities: GSE, ordnance (ORDN), aviation fuel (JP8), and GSE diesel fuel (GSF). The CLF planner can be used to optimize the sustainment of H&S by making use of the following features:

1. Our hub and three spokes play the role of CLF customers (usually battle groups). We code this as follows: LAGBG (Lagos hub), DAKBG (Dakar spoke), ALGBG (Algiers spoke), and DJIBG (Djibouti spoke).

2. Customer tracks (usually given as a daily changing latitude and longitude) become static locations corresponding to the coordinates of the hub and spokes. For example, LAGBG coordinates remain North 06 degrees 27 minutes 23 seconds East 03 degrees 25 minutes 17 seconds for the entire planning horizon.

3. The "Fleet restriction" feature, typically used to prevent certain shuttles from using certain sea routes, is used to separate overland routes for C17 aircraft from sea routes for shuttle ships (Figure 8).

4. Two collocated nodes are created for the MRC in Rota, Spain. These nodes are coded ROTA (for sea shuttles) and ROTAA (Rota Air, for air shuttles).

5. Collocated nodes are also created for selected H&S in order to provide separation amongst air routes. An example of such a node is labeled as follows: ATDJ (Algiers to Djibouti, "Air," see Figure 8), which, combined with the abovementioned fleet restriction, allows only aircraft to proceed via this node. The two arcs associated with the node are a zero-length arc from ALGBG to ATDJ, and a great-circle arc from ATDJ to DJIBG. (Note: Each is a two-way arc.)

The sea and air-route networks regulate the ability of CLF shuttle ships and C17 aircraft to visit each customer multiple times, if needed, and fulfill its demand. Air routes will be able to track directly from the shuttle's home to the customer via a great-circle track. The sea routes, which are incapable of tracking over land, will maintain tracks over water and circle, as needed, in order to reach the customer's port.

ID	Description	Coordinates	Fleet
ABI	Abidjan Ivory Coast	N 05 15 00 W 03 55 48	1
ACOR	A Coruna Spain	N 43 21 47 W 08 23 26	1
ADEN	Aden	N 12 46 48 E 44 58 48	1
ADR	Adriatic Sea	N 42 30 00 E 16 00 00	1
AEG1	Aegis Waypt 1	N 39 10 50 E 25 00 42	1
ALEX	Alexandria Egypt	N 31 10 59 E 29 52 00	1
ALG	Algiers Algeria	N 36 42 02 E 03 12 16	0
ATDJ	Algiers Djibouti Air	N 36 42 02 E 03 12 16	2
ATDA	Algiers Dakar Air	N 36 42 02 E 03 12 16	2
ATLA	Algiers Lagos Air	N 36 42 02 E 03 12 16	2
ARA	Arabian Sea	N 20 00 00 E 60 00 00	1
ATLCPG3	Atlantic Central Passage 3	N 08 03 10 W 27 38 06	1
ATLNR	Atlantic North Route	N 49 01 10 W 29 34 66	1
BALT1	Baltic Sea Waypt 1	N 56 20 29 E 11 57 41	1
BALT2	Baltic Sea Waypt 2	N 55 32 25 E 10 52 13	1
BALT3	Baltic Sea Waypt 3	N 54 36 46 E 10 55 42	1
BALT4	Baltic Sea Waypt 4	N 54 22 02 E 11 48 34	1
BALT5	Baltic Sea Waypt 5	N 54 57 12 E 13 05 47	1
BALT6	Baltic Sea Waypt 6	N 54 30 05 E 14 57 15	1
BALT7	Baltic Sea Waypt 7	N 55 54 03 E 18 51 03	1
BALT8	Baltic Sea Waypt 8	N 58 44 42 E 20 30 50	1
BALTE	Baltic Entry	N 58 07 10 E 10 38 48	1

Figure 8. CLF Planner screenshot for Route Nodes. Port and node accessibility codes ("Fleet") are as follows: 2 for air shuttles, 1 for sea shuttles, and 0 for both shuttles.

14

III. COMBAT LOGISTICS FORCE PLANNER INPUTS

A. BUILDING THE H&S MODEL IN THE CLF PLANNER

Our model uses a network of 108 nodes and 177 undirected arcs (Figure 9), most of which belong to the sea network. As previously defined, our H&S customers are Lagos (LAGBG), Algiers (ALGBG), Dakar (DAKBG), and Djibouti (DJIBG) with Rota (ROTA) and Rota Air (ROTAA), serving as our MRC. Our design is built to utilize C17 aircraft and CLF ships to initiate from or visit the MRC, and distribute logistics and support equipment to each H&S while maintaining their posture in serving the strike groups at sea.
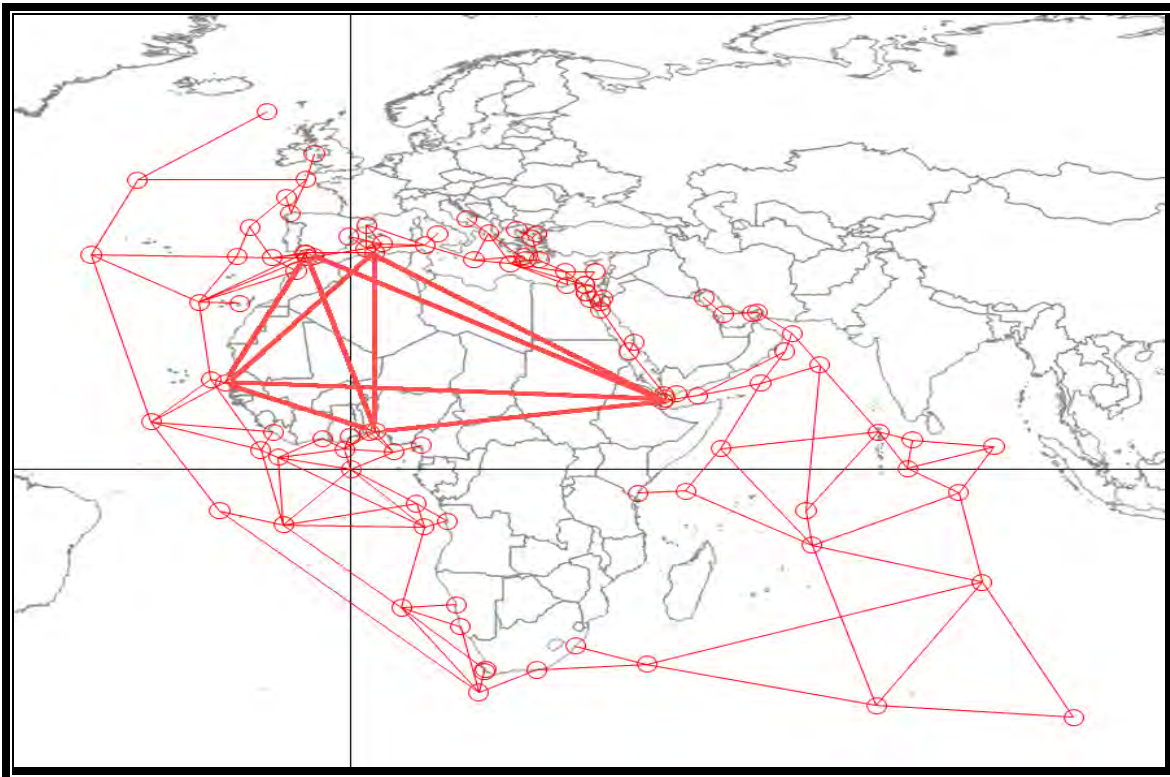
Figure 9. CLF Planner screenshot. The thinner arcs and nodes represent a sea network. The bold arcs represent "air" routes taken by C17 aircraft. CLF ships may visit any node via the depicted sea arcs. The southeastern nodes and arcs appear outside of the AOR but are necessary for the CLF ships to circle the African continent with multiple options, given their initial position.

15

1. Demand Data for Ship Planning Factors

Our scenario data closely resemble operations conducted on MPRA airbases during peacetime operations. These operations are divided into three phases: BuildUp, PreOps, and Sustain. The 45-day demand data for H&S is from CTF-72 (Null, 2010). All fuel data originally provided in gallons is converted into pounds (Table 1) using a conversion factor of 6.7 lbs./gal for JP8 fuel (Petroleum and Water Department, 2003) and 7.002 lbs./gal for GSF.

	JP8 (lbs)	GSF (lbs)	GSE (lbs)	ORDN (lbs)
HUB	78,883,817	3,184,614	1,760,853	5,305,137
SPOKE (each)	53,517,366	3,184,614	1,460,256	3,595,721

Table 1. CTF-72-approved 45-day demand table. Commodities are for JP8, GSF, GSE and ORDN at H&S.

We assume daily demands for the Sustain phase of the operations are the proportional fraction of total demand provided by CTF-72 (i.e., the figures in Table 1 divided by 45 days). Next, we convert all demand data into short-tons and input them into the CLF planner's "ship planning factors" worksheet (Figure 10). However, we also consider PreOps and BuildUp. Our PreOps totals are three-quarters of the daily requirements for sustainment when meeting the JP8 and GSF demands, and one-half of the daily sustainment requirements for GSE and ORDN. The BuildUp demand is set at ten percent of the daily sustainment values for JP8, GSF, and GSE. Lacking a capacity figure for H&S, we assume these as approximately equal to the demand of 22½ days of Sustain operations.

PreOps are usually conducted prior to deployment and at the squadrons' home airbase. However, our PreOps will always occur after an H&S BuildUp. Some of the PreOps activities include crew readiness flights, pilot training flights and carrier strike group coordinated operations. Even though waivers are a viable option, it is beneficial for every squadron to conduct proficiency flights so that each crew maintains readiness and up-to-date qualifications while on deployment. Therefore, the PreOps days will help

satisfy those requirements. Most H&S conduct multiple PreOps in some variation of beginning and/or end-of-the-month flight operations but our scenario assumes only one day for this operation per 45-day cycle.

Ship Planning Factors [Data ▼] ☐ Apply Filters

ShipType	Commodity	Capacity	PreOps	BuildUp	Sustain
HUB	JP8	19,721	657	88	877
HUB	GSF	694	23		31
HUB	GSE	440	10		20
HUB	ORDN	1,326	30		59
SPOKE	JP8	13,379	446	60	595
SPOKE	GSF	694	23		31
SPOKE	GSE	365	8		16
SPOKE	ORDN	899	20		40

Figure 10.   CLF Planner screenshot for daily operations demands (in short-tons) to sustain a hub or spoke. The demands listed are daily estimates for each operation category. For evaluation purposes, the H&S capacity is equivalent to a 22 ½ day Sustain demand.

The BuildUp category represents the initial processes that H&S will complete prior to conducting operations. For BuildUp demands, H&S will provide JP8, GSE, and GSF for transiting aircraft. Each H&S will require a total of seven days to conduct its BuildUp, which we assume occurs on days one through seven for every H&S in our initial scenario. In a different scenario, we will also analyze a 72-hour BuildUp.

2.   Shuttles and Shuttle Classes

The "shuttle classes" worksheet (Figure 11, top) indicates the type of shuttles we utilize for our scenario, and associated data to include the maximum speed (in knots) and the transport capacities of each commodity (in short-tons). Most surface shuttles can deliver heavy loads of JP5 and GSF. However, the JP5 commodity will be replaced with JP8, for our scenario, for planning purposes and analysis. The range of CLF shuttle speeds are from 15 to 25 knots. C17s are assumed to travel at an airspeed of 450 knots. Our scenario uses the following CLF shuttle ships (by classification): six Henry J. Kaiser-

Class Single Hull (TAO-SH), one Auxiliary Cargo and Ammunition Ship (T-AKE), one Combat Stores Ship (T-AFS), two Fast Combat Support Ships (T-AOE), and one United Kingdom's Fort Victoria class replenishment oiler (UK-AORH). We also utilize four C17s as air shuttles.

We use each asset available based on shuttle class (i.e., all 15 shuttles from six classes are scheduled). The CLF ships may either start from a user's predetermined location or a location optimally chosen by the CLF mathematical planner. Each C17's start location is at the user-defined MRC (ROTA). The CLF shuttles' start coordinates are placed at random nodes in our network. Also, each CLF shuttle is distinguished as loaded or not, which we simulate by randomly selecting eight loaded and seven empty ships (Figure 11).

A description of each shuttle class follows. All commodity capacities for the "shuttle classes" worksheet are replicated from previous research using the shuttles in our scenario (Morse, 2008). The Henry J. Kaiser-Class (T-AO) 187 oiler is an 18-ship series (Federation of American Scientists 2010). Their primary objective is to provide underway replenishment of fuel to the U.S. Navy combat ships and JP5 for aircraft aboard aircraft carriers at sea. We classify all our T-AO class shuttles as TAO-SH for CLF planner utilization and one of their commodities, for transport, will be JP8 instead of JP5. Previous studies list TAO-SH as having storage capacities (in short-tons) as follows: 108,520; 220; and 72,000, for JP5, GSE and GSF, respectively. We note these inventory capacities are independent from demand. We insert our own GSF commodity in lieu of the normal diesel fuel marine in the CLF planner. The U.S. inventory for the aforementioned TAO-SH class shuttles includes consecutive hull numbers labeled from T-AO-187 to T-AO-204 except for the T-AO-190 shuttle that was sold in May 2009 and commissioned February 2010 by the Chilean Navy. We have selected six TAO-SH class shuttles to complete our H&S operations.

Some CLF ships are integral parts of the surface battle groups (these are called station ships) and others move logistics supplies from ports, forward logistics sites, or commercial ship "black hulls" to the strike groups at sea (these are called shuttles). The T-AFS class provides logistic lift to deliver cargo (ammunition, food, limited quantities

of fuel, repair parts, ship store items, and expendable supplies and materiel) to U.S. and allied navy ships at sea. In its secondary mission, the T-AKE may have a common plan with a T-AO 187 as a substitute station ship to provide direct logistics support to the ships within a carrier strike group. There are four T-AKE hull numbers conducting operations.

As the Navy's combat logistics role increases throughout the fleet, cost savings are seen each year. One major contributor to the overall minimal cost operation is the T-AOE class. Each of the four existing T-AOEs includes a crew of 160 civilian mariners and 29 military that rapidly replenishes Navy task forces (U.S. Navy, February 2009). T-AOEs are used, in our scenarios, as multi-product shuttles that are capable of carrying heavy loads of each of our commodities to include over 93,000 short-tons of JP8 (our number one prioritized commodity based on demand alone). According to the U.S. Navy fact file, T-AOEs are capable of speeds of 25 knots, which helps resupply transiting carrier strike groups efficiently.

"One combat stores ship operated by Military Sealift Command provides underway replenishment of supplies to Navy combatant ships at sea. Supplies include repair parts, spare parts, food, mail and fuel" (U.S. Navy, February 2009). The T-AFS is one of the CLF shuttles that transports the above supplies. Each T-AFS is composed of 127 civilian mariners and 26 sailors and transits at speeds up to 21 knots (U.S. Navy, August 2009). This shuttle class is in process of being replaced by the T-AKE class but remains active and in the aforementioned configuration for our study.

The UK-AORH class of the Royal Fleet Auxiliary Wave Knight is a fast fleet tanker, and can also store supplies. We hypothesize one shuttle of this class, the UK-AORH-C, as making a port visit at Port Elizabeth South Africa and being called to duty to supply the H&S during the BuildUp and/or Sustain phases. The Wave Knight has a range of 10,000 nautical miles at 15 knots. We assume a cruise speed of 18 knots.

Shuttle Classes [Data ▼]

ID	Description	Speed	JP8	GSE	GSF	ORDN			
TAO_SH	T-AO Single Hull	16	108,520	220	72,000				
TAKE_AFS	T-AKE w/ AFS Load	20	17,000	4,600	7,000	1,010			
TAOE	T-AOE Class	26	93,600	952	62,400	2,016			
TAFS	T-AFS Class	21	10,000	4,600	8,674				
UK_AORH	UK Fort Victoria Class	20	20,966	529	83,850	529			
C17	Globemaster	450	30	35		20			

Shuttles [Data ▼]

ID	Description	Class	Fleet	Speed	Inport	StartDate	StartCoordinates	Loaded
TAO200	AO200 USNS Guadalupe	TAO_SH	1	15	2	1-Nov-09	N 05 15 00 W 03 55 48	x
TAO201	AO201 USNS Patuxent	TAO_SH	1	15	2	7-Nov-09	N 39 55 30 E 25 42 27	
TAFS_WA		TAFS	1	21	1	1-Nov-09	N 12 30 00 E 48 00 00	
TAKE_C	T-AKE 1 USS Lewis & Clark	TAKE_AFS	1	18	1	1-Nov-09	N 46 05 13 W 09 01 13	x
TAOE6	T-AOE 6 USS Supply	TAOE	1	25	2	2-Nov-09	N 35 30 00 E 26 00 00	
TAOE8	T-AOE 8 USS Arctic	TAOE	1	25	2	1-Nov-09	S 12 48 36 E 63 47 44	x
UK_AORH_C	RFA Waveknight	UK_AORH	1	18	1	1-Nov-09	S 33 57 41 E 25 38 11	x
TAO189	AO189 USNS J. Lenthal	TAO_SH	1	15	2	3-Nov-09	N 03 24 36 W 00 52 48	
TAO193	AO193 USNS Walter S. Diehl	TAO_SH	1	15	2	6-Nov-09	N 31 16 12 E 32 19 12	
TAO194	AO194 USNS John Ericsson	TAO_SH	1	15	2	2-Nov-09	N 28 15 00 E 34 30 00	
TAO195	AO195 USNS Leroy Grumman	TAO_SH	1	15	2	2-Nov-09	S 07 00 00 E 62 56 25	
C17_1	First C17	C17	2	450	1	1-Nov-09	N 36 37 12 W 06 21 00	x
C17_2	Second C17	C17	2	450	1	1-Nov-09	N 36 37 12 W 06 21 00	x
C17_3	Third C17	C17	2	450	1	1-Nov-09	N 36 37 12 W 06 21 00	x
C17_4	Fourth C17	C17	2	450	1	1-Nov-09	N 36 37 12 W 06 21 00	x

Figure 11.   CLF Planner screenshot for shuttle inventory. This screenshot combines the "shuttles" and "shuttle classes" worksheets used in the H&S scenario. Each shuttle class has a top speed (CLF ships) and cruise speed (C17 aircraft) in knots. All units for the four commodities are in short-tons and indicate each class' capacity for that commodity. The "shuttles" worksheet displays the transit speeds for the shuttles listed. The time "inport" reflects the amount of time each shuttle must remain at the MRC to restock all commodities. All shuttles become available within seven days. However, their start times and coordinates are varied, as shown.

The four C17s, on deployment, and originating in ROTAA, will serve as the immediate respondent to H&S demands. They are capable of transporting 18 of the 463 L-model pallets that total approximately 85 short-tons of logistics equipment and cargo. According to Boeing airlift business development contact, Colonel Alan K. Baker, U.S. Air Force (retired), the C17 is also capable of carrying standard military fuel bladders for offload of fuel at refueling locations or combat refueling points. Accordingly, we run all scenarios with JP8 as a transport item onboard the C17 aircraft.

The C17 is capable of transporting 9,000 gallons of JP8 fuel via its three 3,000-gallon internal bladders (Petroleum and Water Department 2003). We can use this capacity to transport JP8 fuel on the C17 aircraft, but at the expense of not allowing GSF.

Our rational for this is to indulge the C17 in routine operations for our scenario and keep JP8 our top priority item, as described in the next paragraph.

3. Shuttle Commodities

The shuttle commodities have been prioritized to depict importance of delivery (Figure 12). We have placed the highest penalty, 100, on unmet JP8 to reflect the priority given to fuel in order to fly MPRA. GSE and GSF are given the lowest penalties 20 and 30, respectively, due to the existence of local resources for food and the presence of AIMD to store GSE. We place a penalty of 70 on ORDN based on its importance for missions flown from either hub or spokes that require armament release (although these are more common in a wartime scenario). Also, ORDN has the potential of being flown and released from joint and/or coalition aircraft in the event our MPRA have any ORDN release malfunctions during a mission, or prove a less-capable asset for the sortie being flown.

Once a commodity reaches the "safety-stock" level (50% of its inventory capacity, in our case), the penalty scales are activated. Specifically, when an inventory level falls below this limit, the commodity's multiplicative penalty is inflicted on the magnitude of this shortfall. Moreover, if it falls even further below the "extremis" violation limit (25% of its inventory capacity, in our case), then ten times the penalty is inflicted for the magnitude of this extremis shortfall.

For example, let us consider the inventory capacities at the hub (see Figure 10). These are 19,721 and 1,326 short tons for JP8 and ORDN, respectively. If, for JP8, the inventory falls to 40% of capacity (7,888.4 short tons) then the shortfall with respect to safety-stock level will be 10% (1,972.1 short tons), and the assessed penalty will be 1,972.1×100=197,210. In comparison, the same penalty can be incurred by a remaining inventory of approximately 82.9214 short-tons of ORDN (6.2% of capacity). In this case, since the safety-stock and extremis levels are 663 and 331.5 short-tons, respectively, we would incur the full penalty in the under-safety segment, 331.5×70=23,205, plus a partial penalty in the under-extremis segment, 248.5786×700≈174,005, for a total penalty of 197,210.

Shuttle Commodities [Data ▼]

ID	Description	Penalty
JP8	Aviation fuel (or JP4, JP5, Jet A1)	100
GSE	Parts, Food, Dry Stores (or NC10 & huffer)	20
GSF	GSE fuel (diesel)	30
ORDN	Ordnance (All weapons & explosives)	70

Figure 12. CLF Planner screenshot for shuttle commodities. This allows the planner to prioritize the delivery of each commodity to H&S. The higher the penalty, the more importance is given to the delivery of the commodity. In the given scenario, GSE is the lowest-priority commodity, while JP8 is the highest. (Penalty units are at dollars per short-ton shortage.)

4. Battle Groups and Voyage Plans

Our scenario is designed to provide sustainment for H&S using our CLF shuttles, C17 aircraft and modified C17 carrying ORDN which we denote C17_ORDN aircraft. However, we also explore the shuttles' capability of transporting logistics to H&S as their primary supplier during the BuildUp and Sustain phases on each MPRA base. We model a seven-day BuildUp, a one day PreOps, and then a 37-day Sustain phase. Each of our H&S initiates with zero percent inventory. Our model uses the aforementioned 50% and 25% of the inventory capacity to set the safety stock and extremis thresholds for penalties, respectively (explained in the previous section). Any hub or spoke may be supplied by any shuttle. The H&S play the role of the CLF planner's battle groups but they remain static throughout each scenario (as can be seen by constant coordinates in Figure 13). The "activity" for each day communicates with the Ship Planning Factors worksheet to determine demand values for each commodity on that day.

Battle Groups	Data ▼			Initial Inventory				Safety Stock				Extremis Level			
ID	Description	Ships	Inport	JP8	GSE	GSF	ORDN	JP8	GSE	GSF	ORDN	JP8	GSE	GSF	ORDN
LAGBG	Lagos	LAGBase	1	0%	0%	0%	0%	50%	50%	50%	50%	25%	25%	25%	25%
DAKBG	Senegal	DAKBase	1	0%	0%	0%	0%	50%	50%	50%	50%	25%	25%	25%	25%
ALGBG	Algiers	ALGBase	1	0%	0%	0%	0%	50%	50%	50%	50%	25%	25%	25%	25%
DJIBG	Djibouti	DJIBase	1	0%	0%	0%	0%	50%	50%	50%	50%	25%	25%	25%	25%

BG Voyage Plans   Data ▼   ☐ Apply Filters

BG	Date	Coordinates	Fleet	Activity	HitOK
LAGBG	1-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	2-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	3-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	4-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	5-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	6-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	7-Nov-09	N 06 27 23 E 03 25 17	0	BuildUp	x
LAGBG	8-Nov-09	N 06 27 23 E 03 25 17	0	PreOps	x
LAGBG	9-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	10-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	11-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	12-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	13-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	14-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	15-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	16-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	17-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	18-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	19-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	20-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	21-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	22-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	23-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	24-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	25-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x
LAGBG	26-Nov-09	N 06 27 23 E 03 25 17	0	Sustain	x

Figure 13.　CLF Planner screenshot for battle groups and voyage plans. The Battle Group worksheet displays the initial inventory at each H&S plus the safety stock and extremis levels. Percentages are with regard to the capacity for each commodity (Figure 10). The Battle Group Voyage Plans worksheet shows the activity posture of each H&S on the specified day. That activity communicates with the Ship Planning Factors worksheet (Figure 10) to determine the demand for that day.

B. CLF PLANNER SOLUTION REPORTS

The analysis of results produced by the CLF planner is our basis for deciding whether the sustainment demands for each H&S have been achieved. From running the CLF planner we can observe if the safety-stock or extremis levels (in percentages with respect to total capacity for each commodity) have been violated. There are three forms of output from CLF planner: "battle group daily state," "shuttle schedule," and "log report." In addition, there are two other graphical outputs: map and chart.

23

The Shuttle Schedule (Figure 14) and Battle Group Daily State worksheets' outputs show shuttle activities listed and commodities delivered to each customer. The outputs are similar to an inventory sheet that tracks which shuttle transports the demand from the MRC to the customer. The shuttle schedule output combines multiple inputs such as the shuttle type's storage capacity. The "in-port" days, at the MRC, show visible stock increases for the shuttles being replenished. The screenshot in Figure 14, not particular to our current scenario, gives us an example. As seen on 17-Nov-09, a TAO_M shuttle delivers commodities at ALGBG. As a result, the commodities it carries are used to meet the demand request for ALGBG on that day (not shown in the figure). However, the figure shows the TAO_M transits and proceeds inbound to ROTA within two days to restock the empty GSF commodity and load JP8 to its maximum capacity. The TAO_M shuttles must remain in-port in ROTA for two days before leaving. We see the CLF planners' scheduling output including in-port status, transit time, and execution of on-load and off-load operations.

Shuttle Schedule   ■ Apply Filters

State	Shuttle	Date	Coordinates	Where	JP8	GSE	GSF	ORDN	JP8	GSE
direct	TAO_M	1-Nov-09	N 26 18 00 E 51 30 00		108,520.0	0.0	220.0	0.0		
direct	TAO_M	2-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	3-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	4-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	5-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	6-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	7-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	8-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	9-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	10-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	11-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	12-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	13-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	14-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	15-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_M	16-Nov-09			108,520.0	0.0	220.0	0.0		
hit	TAO_M	17-Nov-09	N 36 42 02 E 03 12 16	ALGBG	108,520.0	0.0	220.0	0.0	2,973.2	0.0
inbound	TAO_M	18-Nov-09			105,546.8	0.0	0.0	0.0		
loading	TAO_M	19-Nov-09	N 36 37 12 W 06 21 00	ROTA	105,546.8	0.0	0.0	0.0		
loading	TAO_M	20-Nov-09	N 36 37 12 W 06 21 00	ROTA	108,520.0	0.0	220.0	0.0		
outbound	TAO_M	21-Nov-09			108,520.0	0.0	220.0	0.0		
outbound	TAO_M	22-Nov-09			108,520.0	0.0	220.0	0.0		
idle	TAO_M	23-Nov-09			108,520.0	0.0	220.0	0.0		
idle	TAO_M	24-Nov-09			108,520.0	0.0	220.0	0.0		
idle	TAO_M	25-Nov-09			108,520.0	0.0	220.0	0.0		
hit	TAO_M	26-Nov-09	N 36 42 02 E 03 12 16	ALGBG	108,520.0	0.0	220.0	0.0	3,567.8	0.0
direct	TAO_M	27-Nov-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	28-Nov-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	29-Nov-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	30-Nov-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	1-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	2-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	3-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	4-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	5-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	6-Dec-09			104,952.2	0.0	35.0	0.0		
direct	TAO_M	7-Dec-09			104,952.2	0.0	35.0	0.0		
hit	TAO_M	8-Dec-09	N 06 27 23 E 03 25 17	LAGBG	104,952.2	0.0	35.0	0.0	10,825.1	0.0
direct	TAO_M	9-Dec-09			94,127.1	0.0	0.0	0.0		
direct	TAO_M	10-Dec-09			94,127.1	0.0	0.0	0.0		
direct	TAO_M	11-Dec-09			94,127.1	0.0	0.0	0.0		
direct	TAO_M	12-Dec-09			94,127.1	0.0	0.0	0.0		
direct	TAO_M	13-Dec-09			94,127.1	0.0	0.0	0.0		
hit	TAO_M	14-Dec-09	N 14 40 56 W 17 25 48	DAKBG	94,127.1	0.0	0.0	0.0	6,303.6	0.0
idle	TAO_M	15-Dec-09			87,823.4	0.0	0.0	0.0		
direct	TAO_L	1-Nov-09	N 12 46 48 E 44 58 48		108,520.0	0.0	220.0	0.0		
direct	TAO_L	2-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_L	3-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_L	4-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_L	5-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_L	6-Nov-09			108,520.0	0.0	220.0	0.0		
direct	TAO_L	7-Nov-09			108,520.0	0.0	220.0	0.0		

Figure 14.　　CLF Planner screenshot for shuttle schedule.　This displays the coordinates, location, and commodity's contents onboard the shuttle for each time step.　Locations labeled with the "BG" suffix are customers, thus their available amounts of each commodity decrease after each visit to that hub or spoke.　Sea shuttles are designed to remain two days in port at the MRC (ROTA) while loading.

　　　　Charts and maps add a convenient visual reference to CLF planner outputs.　The charts show commodity levels over time (examples in the following chapters).　Viewing can be done for one commodity at a time for either "all" H&S or by individual hub or spoke.　The world map can be separated into sections or continents and has an animation option for shuttle locations over time.　Other options allow the user to display route nodes and arcs (Figure 9) or shuttle tracks, among others.

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IV.   MODEL INSIGHTS

A.   OPTIMIZATION SCENARIOS

We have created three scenarios using the five classes of surface shuttles described in section III.A.2 and the C17 air-shuttle class. As a result, we have 11 surface shuttles and 4 air shuttles in each scenario. We assume four CLF shuttles and all C17 shuttles are loaded on the scenario start date. All scenarios assume a 45-day planning horizon, where we set up the following constraints:

- Scenario 1 (S1): Four surface shuttles are pre-loaded and available on day one, and seven more are available on day seven; there is no initial inventory of any commodity at each H&S; all four C17 aircraft are available on the scenario start date; BuildUp occurs on the first seven days followed by PreOps on the eighth day. The remaining days of the planning horizon comprise the Sustain phase.

- Scenario 2 (S2): Same requirements as in S1. However, BuildUp occurs on the first three days followed by PreOps on the fourth day. Then, the Sustain phase begins.

- Scenario 3 (S3): Same requirements as in scenario S2. Four surface shuttles are pre-loaded and available on day one, and seven more are available on the seventh day; there is a 25% initial inventory of all commodities at each H&S; all four C17 aircraft are available on the scenario start date, with three carrying ORDN only. BuildUp occurs on the first three days, followed by PreOps on the fourth day. Then, the Sustain phase begins.

Our scenarios use the CLF planner to provide an indication of our shuttles' ability to assist in maintaining the readiness posture during OPLAN execution. S1 and S2 introduce the concept of "no-fly" days. The no-fly day, for our scenarios, indicates an MPRA is unable to fuel enough JP8 in order to fly one full mission. S3 answers the

question of whether or not a pre-positioned logistics supply significantly contributes to an increase in inventory levels during the sustainment phase.

B.   CLF PLANNER RESULTS

Each scenario has been run on a personal computer with 3.25 GB of RAM at approximately 3.16 GHZ of speed.   CLF Planner uses GAMS/CPLEX (2011) as the solving engine.   Each scenario has approximately 2,000 variables (120 binary) and 2,800 constraints, and runs in approximately 45 minutes to converge within a 1% gap.

1.   S1: Heavy BuildUp

Table 2 shows the percentage of days that the H&S Sustain demands are met in S1. For example, LAGBG, DAKBG and ALGBG meet their ORDN demands during 96%, 67% and 71% of the Sustain phase. With a total of 12 replenishments, DJIBG is the only operational airbase to fulfill its Sustain requirements by maintaining a positive inventory for all commodities during the 37 Sustain days. However, the detailed daily inventory chart for ORDN (Figure 15) shows that there are several days under safety-stock and extremis levels.

We conclude that, because there is no initial inventory of any commodity, each H&S has the potential to experience at least one day in the extremis level for one or more commodities. Most unmet demand (reflected by inventory "levels" strictly below zero) occurs within the buildup phase.

% days H&S Sustain demand met				
H&S	JP8	GSE	GSF	ORDN
LAGBG	100	100	100	96
DAKBG	98	100	98	67
ALGBG	100	100	100	71
DJIBG	100	100	100	100

Table 2.   Percentage of days that H&S demand is met in Scenario S1. This table shows which H&S is achieving its sustainment requirements (even if in a critical state, i.e., extremis level). Approximately 98%–100% of the H&S demands are being met for JP8, GSE, and GSF. DAKBG only achieves a 67% sustainment rate for ORDN.

The following shuttles are notably underutilized:

a. TAO 201: This shuttle has a start date of November 7 (Figure 11) and remains idle throughout the entire scenario. The shuttle does not contribute to reduce unmet demand because the TAO-SH class cannot carry ORDN and the customers are satisfied by other shuttles for all other commodities.

b. TAFS_WA: This shuttle begins on the scenario start date, but it is not loaded. Therefore, it has to travel 10 days from its initial position to ROTA for loading. After two replenishments to ALGBG (the closest spoke from the MRC), it is not used for the last 30 days of the scenario. Like the TAO-SH, this shuttle does not carry ORDN.

c. TAO 189: This shuttle becomes available on November 3, makes one replenishment to ALGBG on December 4, and then remains idle through the end of the horizon.

d. TAO 193, TAO 194, and TAO 195: These shuttles never replenish any hub or spoke.

29

The DJIBG spoke is the major benefactor of CLF shuttle replenishments in S1. DAKBG is the only airbase that does not achieve 100% in JP8 sustainment. This means an alternate aircraft fuel (i.e., JP-4, JP-5, or perhaps JET-A fuel supply from the host-nation's airport) has to be acquired or there will be a no-fly day at that airbase to support its mission set.
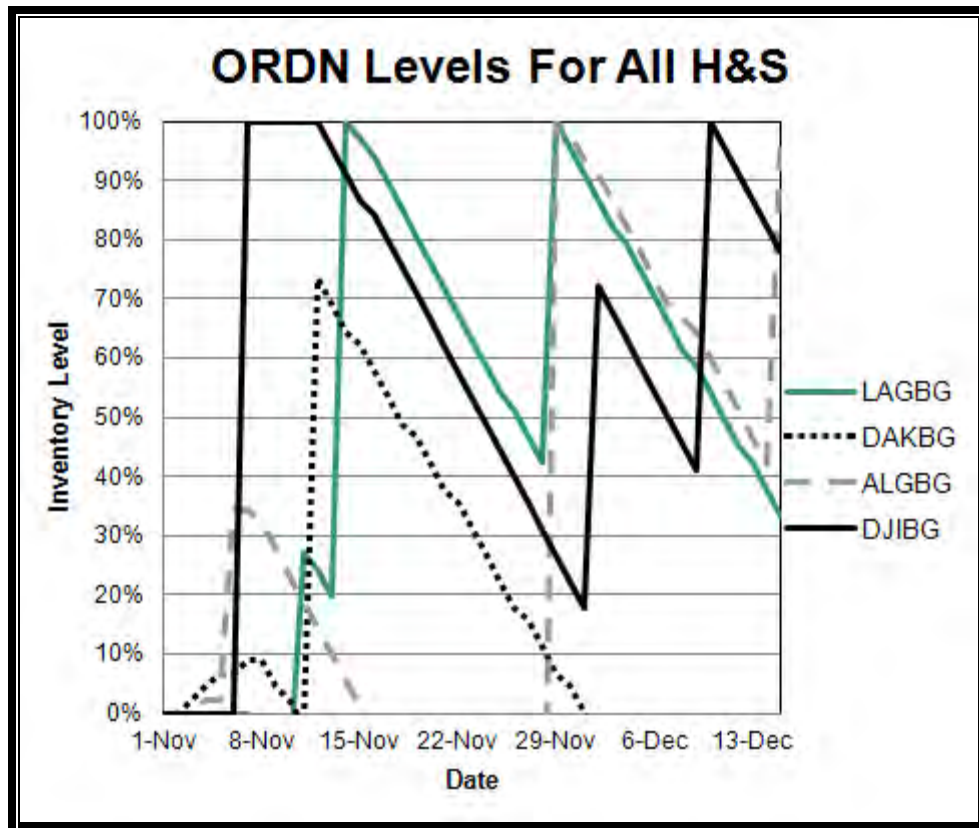

Figure 15.   CLF Planner screenshot for ORDN levels in Scenario S1. November 9 represents the start of the Sustain phase. DJIBG is the only airbase to remain above the 0% Inventory Level for the entire 37-day Sustain phase. LAGBG, DAKBG, and ALGBG maintain a positive inventory level for 96%, 67%, and 71% of their Sustain days, respectively.

2. S2 and S3: Minimum BuildUp

For scenarios S2 and S3, we have created a three-day initial BuildUp phase. S2 is more difficult to sustain due to the earlier demand of four additional Sustain days under the same set-up as for S1. Table 3 displays the percentage of days the H&S meet their Sustain demand in S2.

% days H&S Sustain demand met				
H&S	JP8	GSE	GSF	ORDN
LAGBG	100	100	100	76
DAKBG	87	93	87	82
ALGBG	98	98	98	98
DJIBG	96	96	96	96

Table 3.   Percentage of days that H&S meet their Sustain demand, out of 41 days.

The number of replenishments for H&S in S2 total 24, 16, 22, and 24 for LAGBG, DAKBG, ALGBG, and DJIBG, respectively. Comparatively, S1 provides 18, 17, 15, and 12 replenishments. With JP8 as a transport item onboard C17s, they complete 58% of all replenishment requests. However, C17s are incapable of fulfilling the entire daily H&S demands for commodities they transport (JP8, GSE, and ORDN), thus contributing to the low fulfillment during Sustain days (See Figure 16).
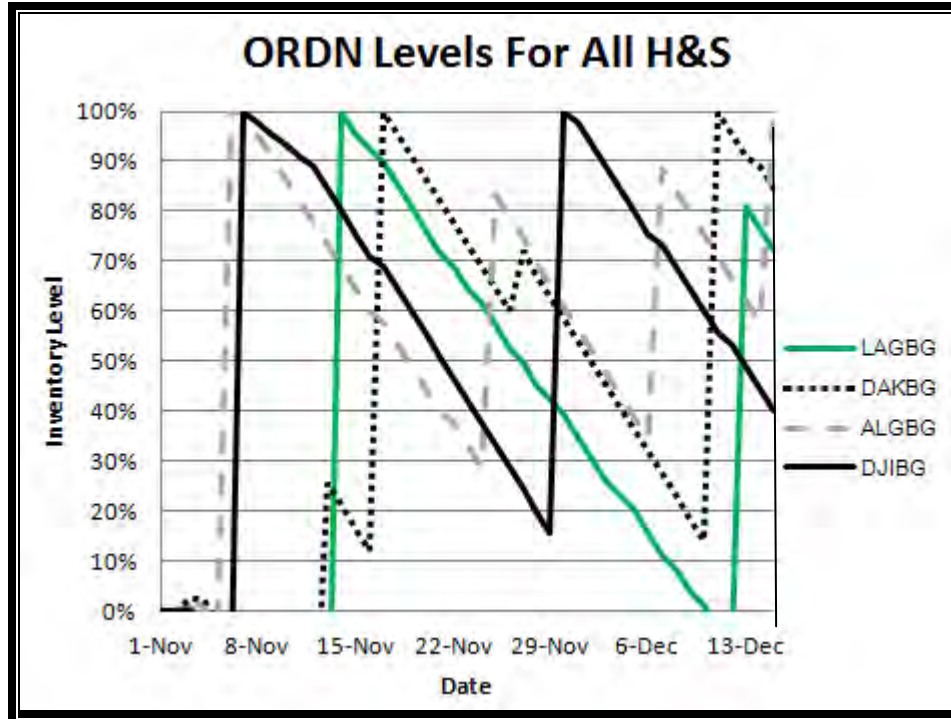
Figure 16.   CLF Planner screenshot for ORDN levels in Scenario S2.   Day four (4-
              Nov) represents the start of Sustain days.   ALGBG and DJIBG achieve
              approximately 98% and 96% daily Sustain success, respectively.   DAKBG
              and LAGBG achieve only 82% and 76%, respectively.

For S3, we create a C17_ORDN shuttle class to carry ORDN, and convert three of
the four aircraft shuttles into this type. We also pre-position 25% initial inventory at our
H&S.   As a result, the CLF planner creates a schedule that satisfies sustainment
requirements for each day of the scenario (Figure 17).   As seen, each H&S remains clear
of the extremis inventory level and rarely reaches an under-safety stock level. S3 proves
to be our most favorable scenario due to the successful sustainment of all commodities.
After observing unmet demand for ORDN in S1 and S2, S3 has been designed to correct
this discrepancy.   It is clear that the addition of C17_ORDN shuttle class and pre-
positioning makes the sustainment phase feasible even with a minimum buildup period.
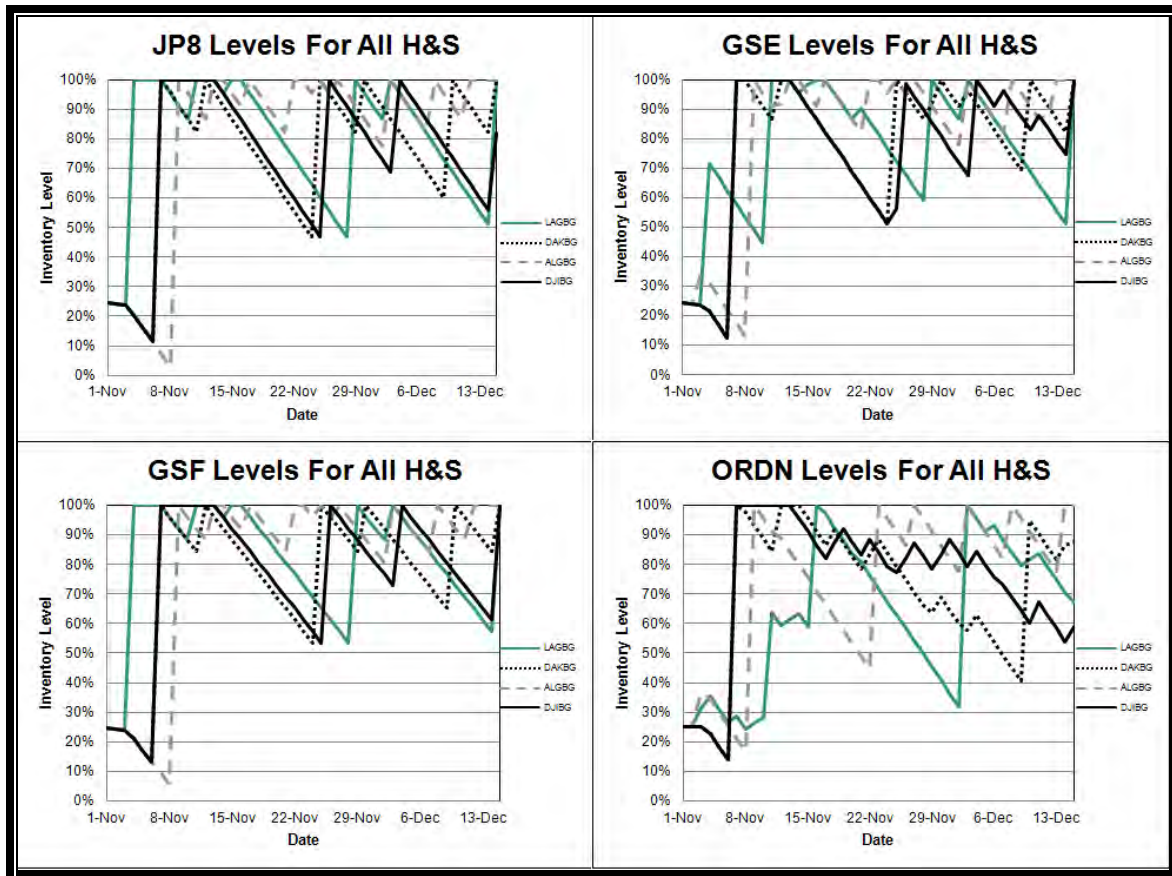
Figure 17.   CLF Planner screenshot for all commodities in Scenario S3.   All H&S achieve 100% operational sustainment. As shown, JP8 and ORDN are the only commodities for which H&S had days below the safety stock region after 8-Nov.

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V.   CONCLUSIONS

This research has studied the ability of CLF ships and C17 aircraft to support buildup and sustainment operations at four MPRA military airbases (Djibouti, Djibouti; Dakar, Senegal; Algiers, Algeria; and Lagos, Nigeria) and one MRC (Rota, Spain). We have implemented a traditional H&S concept with sample demand data from CTF-72.

We have used the CLF Planner, developed by students and faculty at the Naval Postgraduate School, to obtain optimal shuttle schedules for several scenarios. We hypothesize a message received from the Nigerian government requesting military assistance from the U.S.

Our H&S model is a unique application of CLF Planner, which was originally designed for surface shuttle ships supplying underway surface ships. CLF Planner developers have incorporated customized coding in order to avoid ships transiting on air routes and aircraft flying any profile other than point-to-point.

CLF Planner uses multiple data inputs to specify the sea routes and point-to-point air routes that service our H&S customers. We have represented the region's navigation and aviation routes using 108 nodes and 177 arcs. We have also represented 15 CLF shuttles (11 vessels and 4 aircraft). At the beginning of the planning horizon, all of these shuttles have been randomly positioned throughout the AOR and used to convey the four commodities required at the H&S: JP8, GSF, GSE, and ORDN.

We have tested three scenarios, S1, S2, and S3, respectively, for daily demands of each of the commodities over a 45-day planning horizon. We assume a minimum safety-stock level is reached whenever the inventory falls below 50% of a commodity's total capacity, or an extremis level of 25%. CLF Planner has produced results for each scenario from which decision makers may gain important insights in the planning of the operations supported from H&S.

In Scenario S1, entitled "Heavy BuildUp," we start with an empty airbase that needs to be built into an operational hub or spoke that is capable of continued sustainment of the various MPRA missions. The buildup phase consists of the first seven

days where no airbase (LAGBG, DAKBG, ALGBG nor DJIBG) has an initial stock of any commodity. CLF Planner produces a feasible outcome that could, presumably, be considered successful by many commanders: Even though it leaves a modest amount of unmet demand of ORDN, it meets 100% of the demands for the JP8, GSE, and GSF commodities (for all but DAKBG, which still achieves 98% sustainment for both JP8 and GSF). While some shuttles work expeditiously in order to fulfill H&S's demands, the TAO_SH class shuttles are used only modestly because they cannot carry ORDN (and therefore they cannot help reduce the unmet demand for this commodity). The rest of the unmet demand is due solely to long transit times for all CLF ships.

Scenarios S2 and S3 are both referred to as "Minimum BuildUp" because we assume the buildup phase must be completed in only three days. All other requirements for S2 are the same as for S1. Our computational results show the minimum buildup period makes the sustainment phase even more difficult. The H&S spend more days in the extremis level for S2 in comparison to S1. Also, LAGBG is the only hub or spoke to achieve 100% sustainment for three of four commodities.

S3 also starts with a minimum buildup period. However, we assume dedicated ORDN air shuttles and pre-positioning of commodities at the extremis level. No demand is left unmet for any day during the sustainment phase. Thus, we recommend this scenario for H&S operations.

We have demonstrated the use of the CLF Planner as an H&S model to show the importance of pre-staging commodities and dedicating certain shuttles. This changing of planning assumptions and quickly testing logistic feasibility can be applied across a range of scenarios in various regions. Future research may test new scenarios where, for example: (a) All CLF shuttles, instead of the four used for our scenario, are preloaded in order to prevent the initial trip to the MRC; and, (b) Compare with manually developed plans where, for example, some of the CLF shuttles are "geographically" dedicated to certain customers.

Also, we recommend the addition of the CLF planner into the U.S. Navy's "Collaboration at Sea" website for planning purposes.

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